ZOOPLANKTON SAMPLING WITH NETS AND TRAWLS

P. H. Wiebe, Woods Hole Oceanographic Institution, Woods Hole, MA, USA
M. C. Benfield, Louisiana State University, Baton Rouge, LA, USA

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Introduction

In the late 1800s and early 1900s, quantitative ocean plankton sampling began with non-opening/closing nets, opening/closing nets (mostly messenger-based), high-speed samplers, and planktobenthos net systems. Technology gains in electrical/electronic systems enabled investigators to advance beyond simple vertically or obliquely towed nets to multiple cod-end systems and multiple net systems in the 1950s and 1960s. Recent technological innovation has enabled net systems to be complemented or replaced by optical and acoustics-based systems. Multi-sensor zooplankton collection systems are now the norm and in the future, we can anticipate seeing the development of real-time four-dimensional plankton sampling and concurrent environmental measurements systems, and ocean-basin scale sampling with autonomous vehicles.

From the beginning of modern biological oceanography in the late 1800s, remotely operated instruments have been fundamental to observing and collecting zooplankton. For most of the past century, biological sampling of the deep ocean has depended upon winches and steel cables to deploy a variety of instruments. The development of quantitative zooplankton collecting systems began with Victor Hensen in the 1880s (**Figure 1A**). His methods covered the whole scope of plankton sampling from the building and handling of nets to the final counting of organisms in the laboratory.

Three kinds of samplers developed in parallel: waterbottle samplers that take discrete samples of a small volume of water (a few liters), pumping systems that sample intermediate volumes of water (tens of liters to tens of cubic meters), and nets of many different shapes and sizes that are towed vertically, horizontally, or obliquely and sample much larger volumes of water (tens to thousands of cubic meters) (**Table 1**). Net systems dominated the equipment normally used to sample zooplankton until recent technological developments enabled the use of high-frequency acoustics and optical systems as well.

Net Systems

A variety of net systems have been developed over the past 100 + years and versions of all of these devices are still in use today. They can be categorized into eight groups: non-opening/closing nets, simple opening/closing nets, high-speed samplers, neuston samplers, planktobenthos plankton nets, closing cod-end samplers, multiple-net systems, and moored plankton collection systems.

Non-opening/Closing Nets

Numerous variants of the simple non-opening/closing plankton net have been developed, which are principally hauled vertically. Most are simple ring-nets with mouth openings ranging from 25 to 113 cm in diameter and conical or cylinder-cone nets 300–500 cm in length. Among the ring-nets that have been widely used are the Juday net (**Figure 1B**), International Standard Net, the British N-series nets, the Norpac net, the Indian Ocean Standard net (**Figure 1C**), the ICITA net, the WP2 net, the CalCOFI net, and the MARMAP Bongo net (**Figure 1D**). Early nets were made from silk, but today nets are made from a square mesh nylon netting. Typical meshes used on zooplankton nets range from 150 μm to 505 μm, although larger and smaller mesh sizes are available. Most of these nets are designed to be hauled vertically. They are lowered to depth cod-end first and then pulled back to the surface with animals being caught on the way up. Others, such as the CalCOFI net and the Bongo net are designed to be towed obliquely from the surface down to a maximum depth of tow and then back to the surface. The Reeve net was a simple ring-net with a very large cod-end bucket designed to capture zooplankton alive. The Isaacs-Kidd midwater trawl (IKMT) has been used to collect samples of the larger macrozooplankton and micronekton. It has a pentagonal mouth opening and a dihedral depressor vane as part of the mouth opening. Four sizes of IKMTs, 3 foot (91 cm), 6 foot (183 cm), 10 foot (304 cm), and 15 foot (457 cm) are often cited.

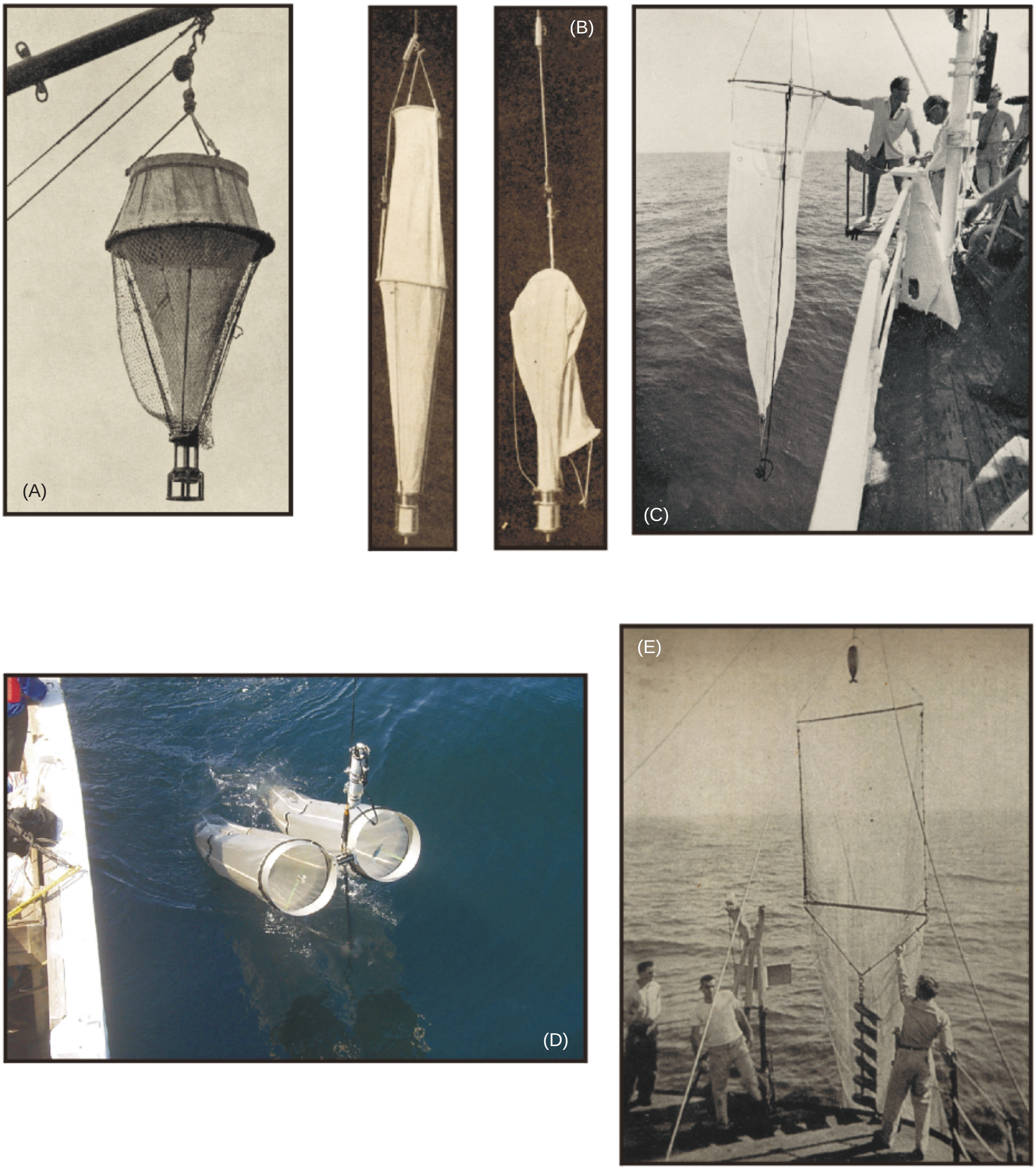

Figure 1 Some commonly used non-opening/closed nets. (A) The Hensen net. (Reproduced with permission from Winpenny, 1937.) (B) The Juday net; note the use of messenger release on this version of the net. (Reproduced with permission from Juday, 1916.) (C) The Indian Ocean Standard net. (Reproduced with permission from Currie, 1963.) (D) The Bongo net with CTD (*c.* 1999). (Photograph courtesy of P. Wiebe.) (E) The Tucker trawl. (Reproduced with permission from Tucker, 1951.)

Non-opening/closing nets with rectangular mouth openings were not widely used until the Tucker trawl was first described in 1951 (**Figure 1E**). This simple trawl design with a 180 cm × 180 cm mouth opening gave rise to a substantial number of opening/closing net systems described below.

Simple Opening/Closing Nets

The development of nets that could obtain depth-specific samples evolved from those of very simple design (a simple ring net) at an early stage. In the late 1800s and early 1900s, there was considerable

Table 1 Summary of zooplankton sampling gear types

Sampling gear	*Type of sampling*	*Size fraction*	*Resolving scale*		*Typical operating range*	
			Vertical	*Horizontal*	*Vertical*	*Horizontal*
Conventional methods						
Waterbottles	Discrete samples	Micro/meso	0.1–1 m	—	4000 m	—
Small nets	Vertically integrating	Micro/meso	5–100 m	—	500 m	—
Large nets	Vertical, obliquely Horizontally integrating	Meso/macro	5–1000 m	50–5000 m	1000 m	10 km
High-speed samplers	Obliquely, horizontally integrating	Meso/macro	5–200 m	500–5000 m	200 m	10 km
Pumps	Discrete samples	Micro/meso	0.1–100 m	—	200 m	—
Multiple net systems						
Continuous plankton recorder	Horizontally integrating	Meso	10–100 m	10–100 m	100 m	1000 km
Longhurst-Hardy plankton recorder	Obliquely, horizontally integrating	Meso	5–20 m	15–100 m	1000 m	10 km
MOCNESS	Obliquely, horizontally integrating	Meso/macro	1–200 m	100–2000 m	5000 m	20 km
BIONESS	Obliquely, horizontally integrating	Meso/macro	1–200 m	100–2000 m	5000 m	20 km
RMT	Obliquely, horizontally integrating	Meso/macro	1–200 m	100–2000 m	5000 m	20 km
Multinet	Vertically Obliquely, horizontally	Meso/macro	2–1000 m	100–2000 m	5000 m	5 km
Electronic optical or acoustical systems						
Electronic plankton-counter	High resolution in the horizontal/vertical plane	Meso	0.5–1 m	5–1000 m	300 m	100s of km
In situ silhouette camera net system	High resolution in the horizontal/vertical plane	Meso	0.5–1 m	5–1000 m	1000 m	10 km
Optical plankton counter	High resolution in the horizontal/vertical plane	Meso	0.5–1 m	5–1000 m	300 m	100s of km
Video plankton recorder	High resolution in the horizontal/vertical plane	Meso	0.01–1 m	5–1000 m	200 m	100s of km
Ichthyoplankton recorder	High resolution in the horizontal/vertical plane	Meso	0.1–1 m	5–1000 m	200 m	10 km
Multifrequency acoustic profiler system	High resolution in the horizontal/vertical plane	Meso/macro	0.5–1 m	5–1000 m	100 m	10 km
Dual-beam acoustic profiler	High resolution in the horizontal/vertical plane	Meso/macro	0.5–1 m	1–1000 m	800 m	100s of km
Split-beam acoustic profiler	High resolution in the horizontal/vertical plane	Meso/macro	0.5–1 m	1–1000 m	1000 m	100s of km
ADCP	High resolution in the horizontal/vertical plane	Meso/macro	10 m	5–500 m	500 m	100s of km

Most vertical nets are hauled at a speed of 0.5–1 $m\,s^{-1}$. Normal speed for horizontal tows are $\sim$2 knots (1 $m\,s^{-1}$) and for high-speed samplers $\sim$5 knots (2.6 $m\,s^{-1}$). For further categorization of pumping systems which are used by a number of investigators, reference is made to the review paper by Miller and Judkins (1981).

(Reproduced with permission from Sameoto D, Wiebe P, Runge S *et al*. (2000) Collecting zooplankton. In: Harris R, Wiebe P, Lenz J, Skjoldal HR and Huntley M (eds) *ICES Zooplankton Methodology Manual*, pp. 55–81. New York: Academic Press.)

effort to develop devices that closed or opened and closed nets at depth. Most employed mechanical release devices which were attached to the towing wire and activated by messengers traveling down the towing wire. The single-messenger Nansen closing mechanism and its variants were very popular during most of early to mid-twentieth century (**Figure 2A**). Double-messenger systems that opened and then closed a net quickly followed. In the mid-1930s, the Leavitt net system became popular and variants of this system are still being used today (**Figure 2B**). Another popular system still in use today is the Clarke and Bumpus sampler, a two-messenger zooplankton collection system that can be deployed as multiple units on the wire and has a positive means of opening and closing the mouth of the net (**Figure 2C**).

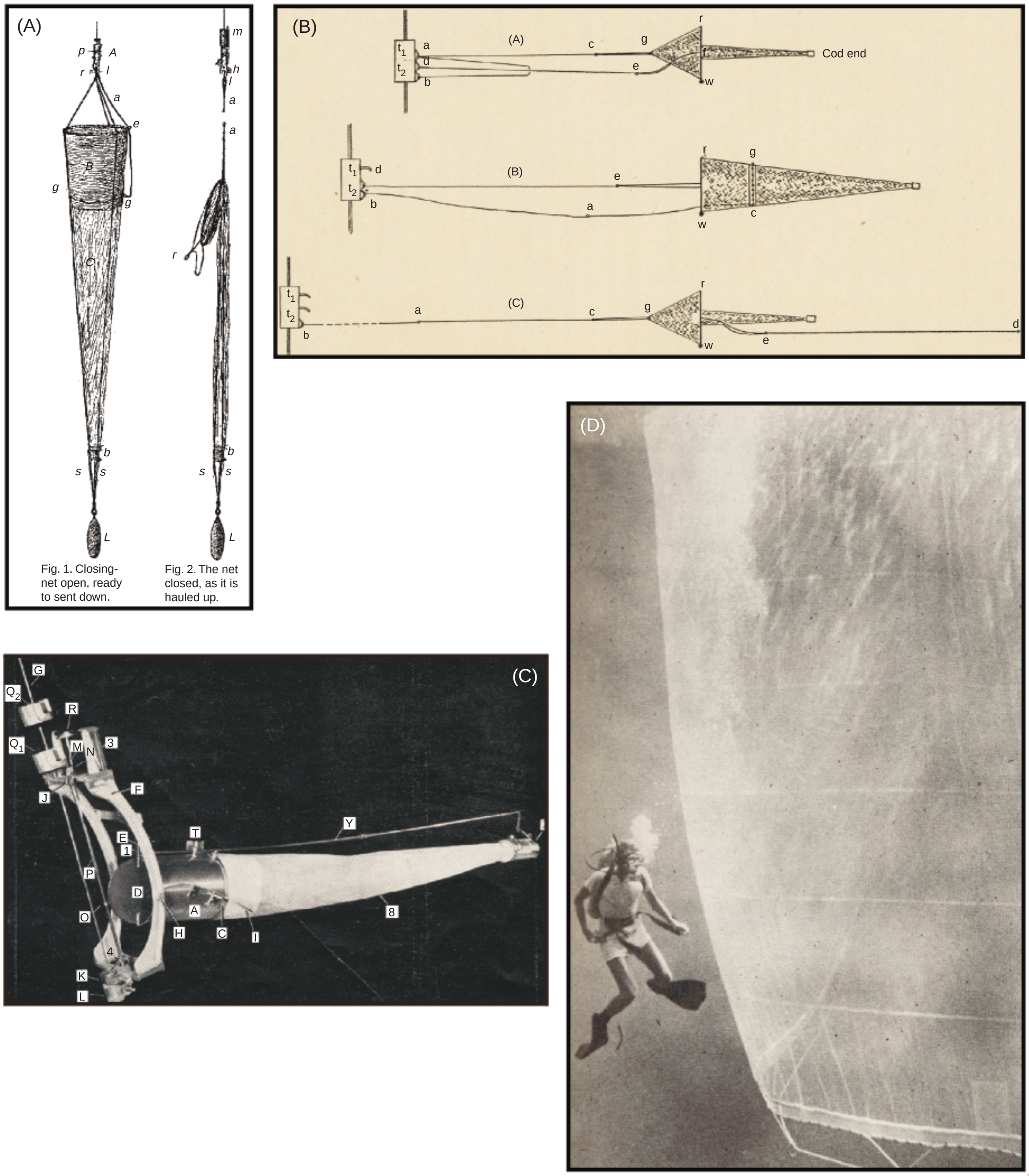

Figure 2 Some commonly used simple opening/closing nets. (A) The single-messenger Nansen closing net. (Reproduced with permission from Nansen, 1915.) (B) The two-messenger Leavitt net. (Reproduced with permission from Leavitt, 1935.) (C) The two-messenger Clarke-Bumpus net. (Reproduced with permission from Clarke and Bumpus, 1939.) The plankton purse seine (D) represents an unusual way to collect plankton from a specific region. (Reproduced with permission from Murphy and Clutter, 1972.)

Mechanical tripping mechanisms activated by pressure, by combinations of messengers and flow-meter revolutions, or clocks have also been devised.

Nontraditional approaches to collecting plankton include designs to catch plankton on the downward fall of the net rather than the reverse – so-called pop-down nets; to sample under sea ice using the English umbrella net; to sample plankton from several depths simultaneously, using a combination of nets and a pumping system; to sample plankton from the nuclear submarine, *SSN Seadragon*; to open and close a Tucker-style trawl using two towing cables, one for the top spreader bar and one for the bottom, with each cable going to a separate winch; and to capture plankton and fish larvae with a plankton purse seine (**Figure 2D**).

High-speed Samplers

Most of the net systems described above were towed at speeds <3 knots ($150\,cm\,s^{-1}$). High-speed samplers typically towed at speeds of 3–8 knots ($150–400\,cm\,s^{-1}$) were also developed in the late 1800s and early 1900s to sample in bad weather, for underway sampling between stations, or to reduce the effects of net avoidance by the larger zooplankton. The Hardy plankton indicator, developed in the 1920s, was the first widely used device. The original version was 17.8 cm in diameter and 91.4 cm in length with a circular filtering disk on which plankton were collected. It was subsequently modified (and renamed the standard plankton indicator) to make it smaller, more streamlined, and equipped with a depressor and stabilizing fins (**Figure 3A**). An even smaller version, the Small Plankton Sampler, was developed. In the 1950s, it was further modified and named the Small Plankton Indicator, and in the 1960s, it was modified again so that multiple units could be used on the towing wire at speeds of 7–8 knots with a multiplane kit otter depressor at the end of the wire. Until the 1950s, only one high-speed collector was designed with a double-messenger system that enabled the mouth to be opened and closed; most could not make depth-specific collections.

The 'Gulf' series of high-speed samplers developed in the 1950s and early 1960s gave rise to a number of high-speed samplers still in use today. The first was the Gulf I-A which looked similar to earlier high-speed samplers. The Gulf III was a much larger high-speed sampler that was enclosed in a metal case. The Gulf V was an unencased and scaled-down version of the Gulf III (**Figure 3B**). The Gulf III and Gulf V samplers have been very popular, and have been modified numerous times. In the early 1960s, a five-bucket cod-end sampling device was added to the Gulf III that was electrically activated from a deck unit through two-conductor cable. HAI (shark) was the German version of the Gulf III built in the mid-1960s. A hemispherical nose cone and an opening/closing lid were added to the HAI. This German system evolved further when 'Nackthai' (naked shark), a modified Gulf V sampler, was developed in the late 1960s. Also in the 1960s, the British modified the Gulf III sampler, which was subsequently called the Lowestoft sampler (**Figure 3C**). Subsequently, the Lowestoft sampler was scaled down and made opened bodied; hence it became a modified Gulf V. The Ministry of Agriculture, Fisheries and Food MAFF/Guildline high-speed samplers, developed in the 1980s, were also modified Lowestoft samplers. These systems have a Guildline CTD sensor unit with oxygen, pH, and digital flowmeter as additional probes with telemetry through a conducting cable. Recently in the 1990s, the Gulf VII/Pro net and MAFF/Guildline high-speed samplers were developed that are routinely towed at 5–7 knots.

Other high-speed samplers were developed during the 1950s and 1960s, including a high-speed plankton sampler which could collect a series of samples during a tow; the 'Bary Catcher' that had an opening/closing mechanism in the mouth of the sampler (**Figure 3D**); a vertical high-speed sampler with a rectangular mouth opening that could be closed using the Juday method; an automatic high-speed plankton sampler with 21 small nets that were sequentially closed by means of a cam/screw assembly driven by a ships log (propellor); and the Clarke Jet net that was an encased high-speed sampler with an elaborate internal passageway designed to reduce the flow speed of water within the sampler to that normally experienced by a slowly towed net.

The continuous plankton recorder (CPR) is in a class by itself when it comes to high-speed plankton samplers, because it can take many samples and can be towed from commercial ships (**Figure 3E**). Originally built in the 1920s, it has evolved over the years to become the mainstay in a plankton survey program in the North Atlantic. This encased sampler weight 87 kg and is about 50 cm wide by 50 cm tall by 100 cm long. The $1.27\,cm \times 1.27\,cm$ rectangular aperture expands into a larger tunnel opening. The tunnel passes through the lower portion of the sampler and out of the back. Below the tunnel is one spool of silk gauze which threads across the tunnel and captures the plankton. A second spool of silk gauze lies above the tunnel and is threaded to meet the first gauze strip as it leaves the tunnel, sandwiching the plankton between the two strips. The gauze strips are wound up on a take-up spool which resides in a formalin-filled tank above the flow-through tunnel, preserving the plankton. The take-up spool is driven by a propellor on the back of the sampler behind the tail fins. This sampler is usually towed at 20 knots from commercial transport vessels at a fixed depth of about 10 m below the surface, thus it only samples the surface layer of the ocean. The undulating oceanographic recorder (UOR) was developed in the 1970s to extend the vertical sampling capability of high-speed plankton collection systems. The UOR carries sensors to

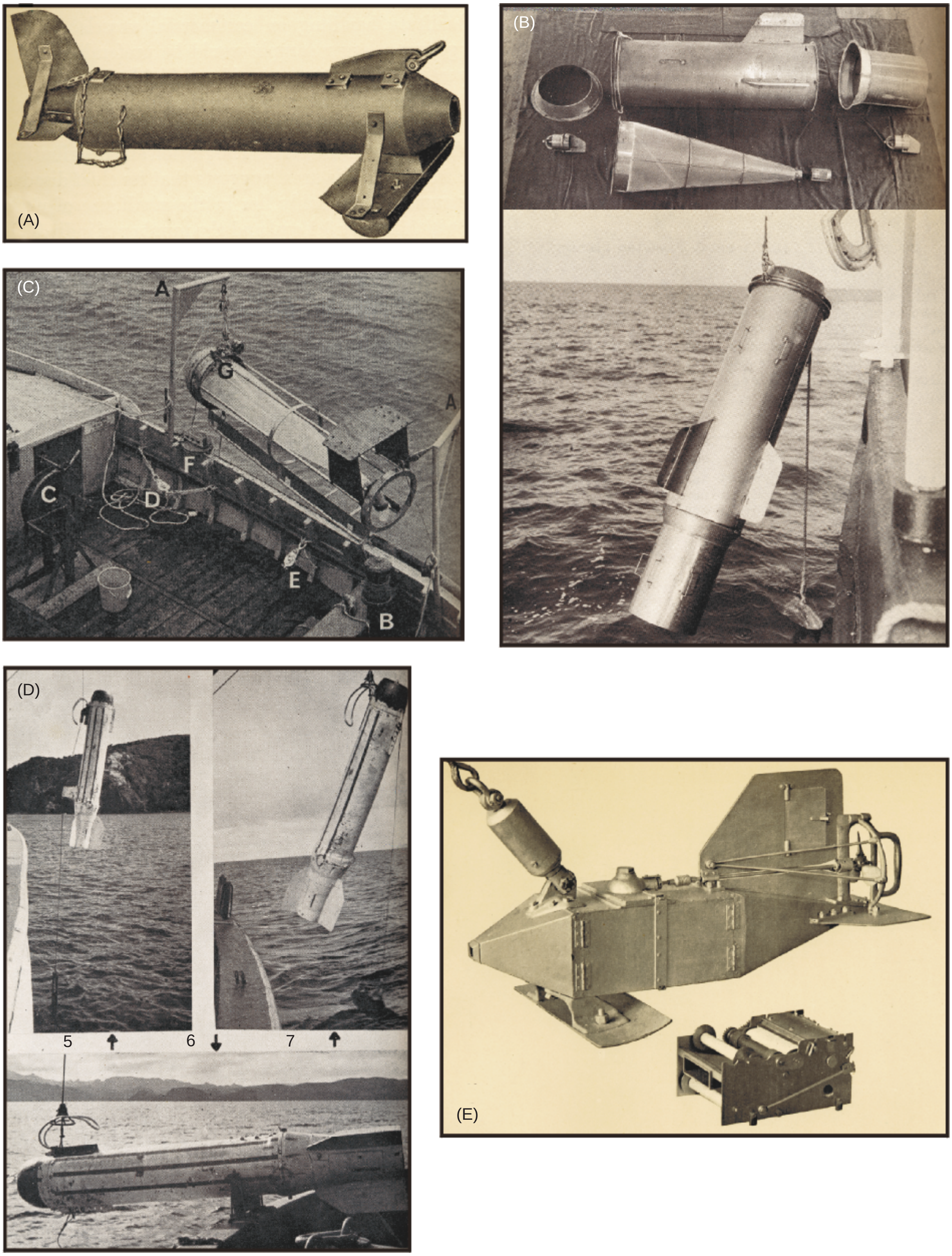

Figure 3 Some examples of high-speed plankton samplers. (A) The standard plankton indicator. (Reproduced with permission from Hardy, 1936.) (B) The encased Gulf III sampler. (Reproduced with permission from Gehringer, 1952.) (C) The open-bodied Lowestoft sampler (Gulf V type). (Reproduced with permission from Lockwood, 1974.) (D) The Bary catcher. (Reproduced with permission from Bary, 1958.) (E) The continuous plankton recorder (CPR). (Reproduced with permission from Hardy, 1936.)

measure temperature, salinity, and pressure; data are logged internally at 30 observations per minute. A propellor drives the rollers winding up the gauze and provides the power for the electronics.

Neuston Samplers

Nets to collect neuston, the zooplankton that live within a few centimeters of the sea surface, by-and-large are non-opening/closing. The first net specifically designed to sample zooplankton neuston was built in about 1960. A rectangular mouth opening design is typical of most of the systems. Neuston nets come either with a single net which collects animals right at the water surface or vertically stacked sets of two to six nets extending from the surface to about 100 cm depth (**Figure 4**). Normally they are towed from a vessel, but a 'push-net' was developed in the 1970s with a pair of rectangular nets positioned side-by-side in a framework and mounted in front of a small catamaran boat that pushed the frame through the water at ~ 2.6 knots.

Planktobenthos Plankton Nets

The ocean bottom is also special habitat structure for zooplankton, and gear to sample zooplankton living here ('planktobenthos') was developed early. The first nets were designed in the 1890s specifically to sample plankton living very near the bottom. Non-opening/closing systems were succeeded by samplers with mechanically operated opening/closing doors or with a self-closing device (**Figure 5A**).

An entirely different strategy has been to employ manned submersibles or deep-towed vehicles to collect deep-sea planktobenthos. A pair of nets mounted on the front of DSRV *Alvin* was used for making net collections at depths > 1000 m in the 1970s; the pilot opened and closed the net (**Figure 5B**). A multiple net system was used on the Deep-Tow towed body. This system was attached to the bottom of the Deep-Tow and used for sampling within a few tens of meters above the deep-sea floor in the 1980s (**Figure 5C**). This net system was later adapted for use on DSRV *Alvin* for near-bottom studies of plankton in the vicinity of hydrothermal vent sites in the 1990s.

On other benthic habitats, such as coral reefs, fixed or stationary net systems which orient to the current's flow and filter out zooplankton drifting by, nets pushed by divers, and traps have been used to capture plankton close to the bottom. The Horizontal Plankton Sampler (HOPLASA) creates its own current to collect zooplankton on or near the bottom in coral reef areas with variable or little current flow (**Figure 5D**).

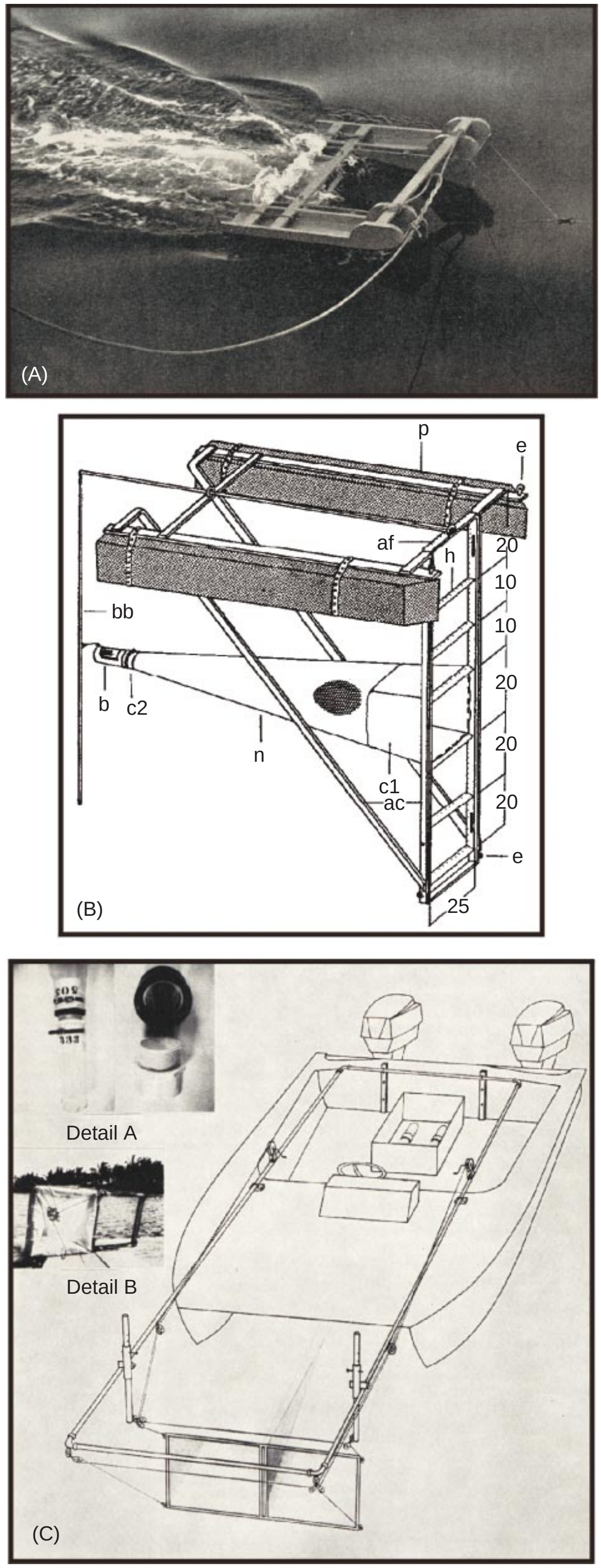

Figure 4 Neuston net samplers collect plankton living at the sea surface. (A) A single net system. (Reproduced with permission from David, 1965.) (B) A multinet system. (Reproduced with permission from Ellertsen, 1977.) (C) A push net. (Reproduced with permission from Miller, 1973.)

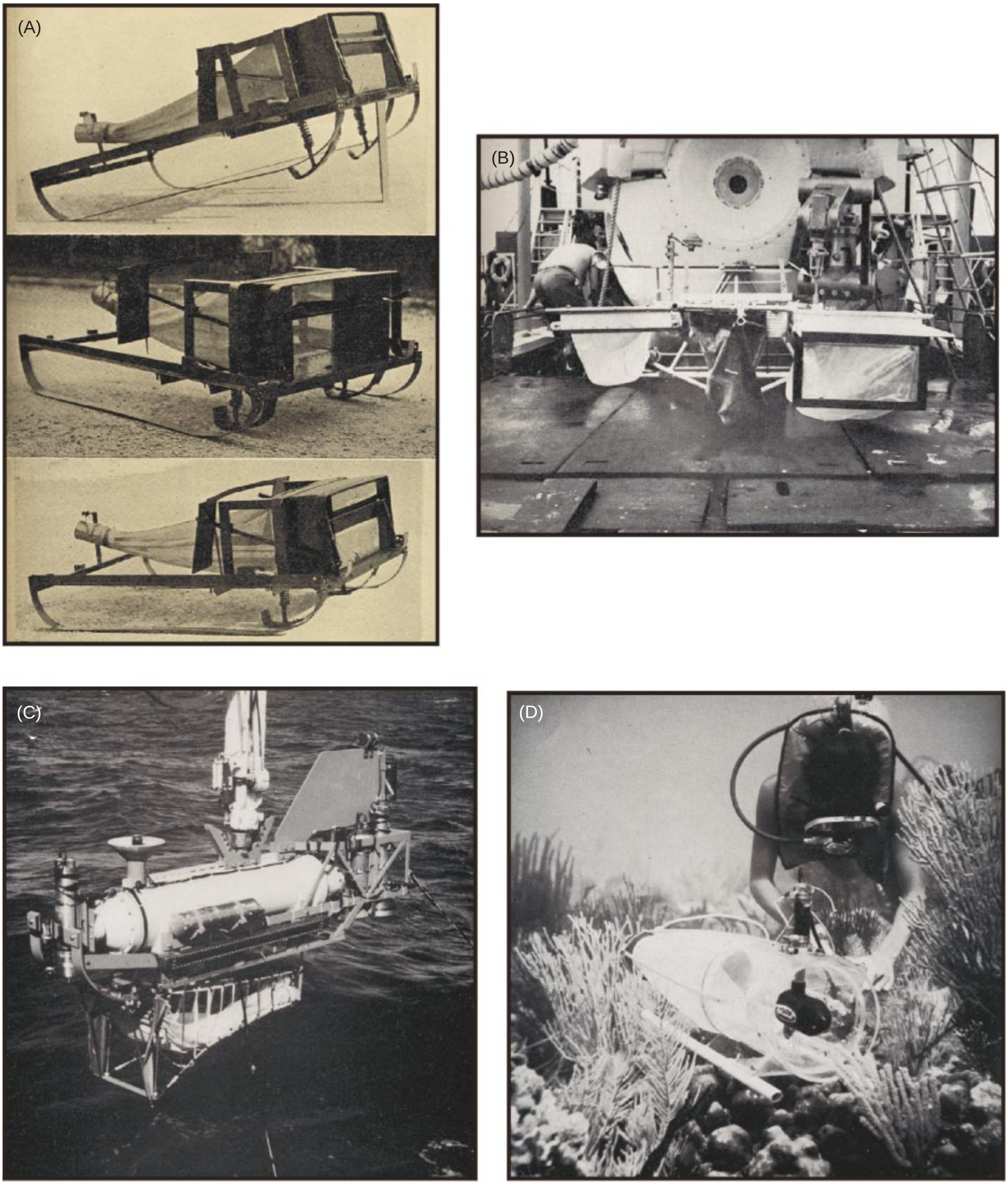

Figure 5 Some planktobenthos samplers. (A) Early system with opening/closing doors. (Reproduced with permission from Wickstead, 1953.) (B) DSR Alvin opening/closing system. (Reproduced with permission from Grice, 1972.) (C) The Deep-Tow multiple net system. (Reproduced with permission from Wishner, 1980.) (D) A system for coral reef sampling (HOPLASA). (Reproduced with permission from Rutzler, 1980.).

Closing Cod-end Systems

In the late 1950s and 1960s, conducting cables and ransistorized electronics were beginning to be adapted for oceanographic use and sophisticated net systems began to do more than collect animals at specific depth intervals. Single nets equipped with closing cod-end devices preceded multiple net systems by only a few years. One of the first systems used a 1950s version of a serial device in the high-speed sampler that was mechanically driven by a propellor. Another had a pressure-actuated catch-dividing bucket (CDB) attached to the back of an IKMT (**Figure 6A**). The Mark III Discrete Depth Plankton Sampler (DDPS) also developed for use with an IKMT or a 1 m diameter net, had four catch chambers separated by solenoid-activated damper doors (**Figure 6B**). This latter system was one of the first to carry underwater electronics to sample depth and temperature, and to telemeter the data up a single conductor cable for display at the surface. The multiple plankton sampler (MPS, described below) was turned into a cod-end sampler for an IKMT and later modified by adding environmental sensors and an electronically controlled opening/closing mechanism.

The Longhurst-Hardy plankton recorder (LHPR), a modification of the CPR, was developed in the 1960s (**Figure 6D**). The recorder box was attached to the back end of a net and gauze strips in the box were advanced in discrete steps (15 s to 60 s) by an electronics package on the tow frame; data on pressure, temperature, and flow were logged on an internal recorder; power was supplied by a NICAD battery pack. The LHPR was redesigned in the 1970s to reduce problems with hang-ups and

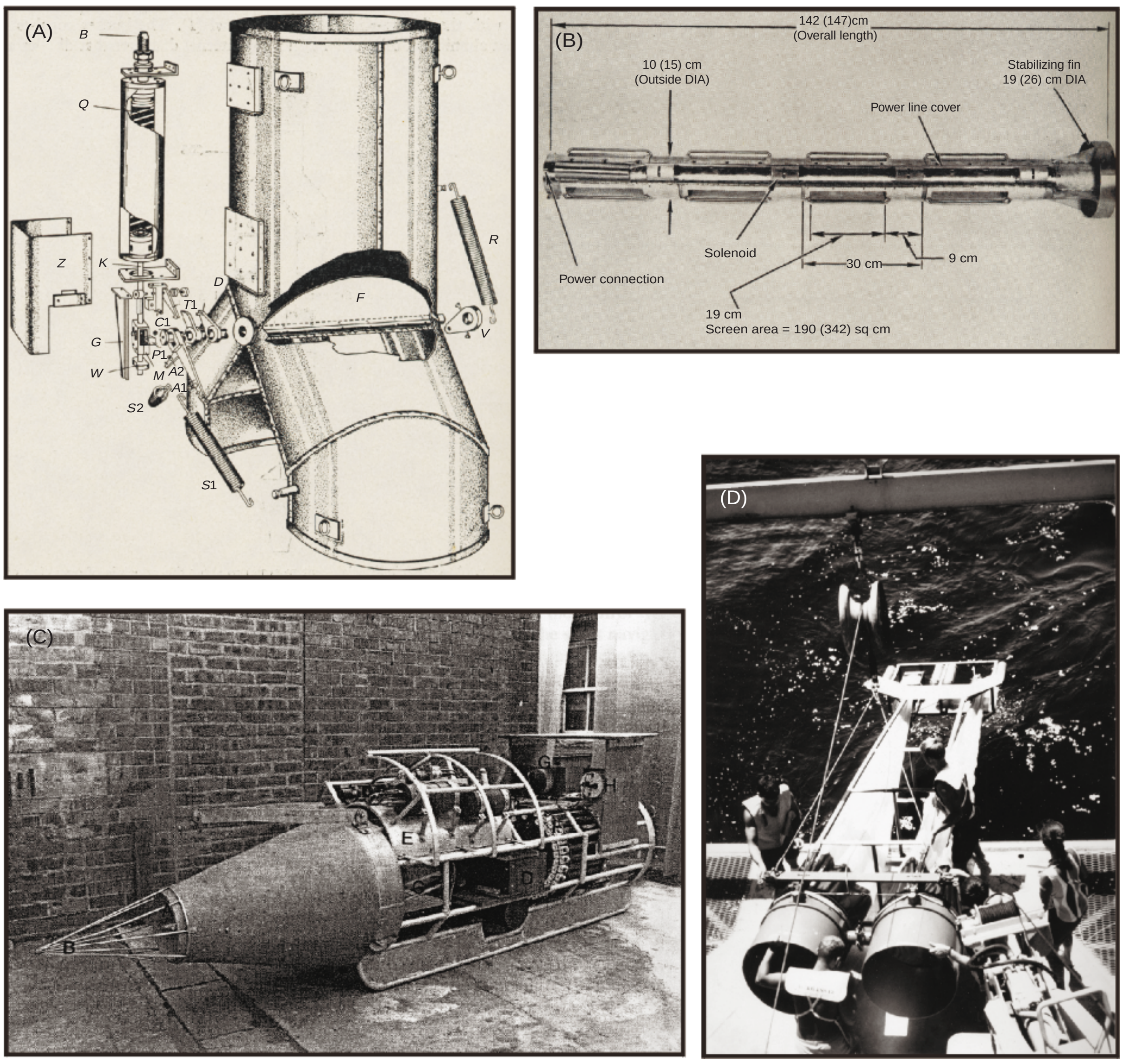

Figure 6 Some discrete-depth samplers using a closing cod-end. (A) The catch dividing cod-end. (Reproduced with permission from Foxton, 1963.) (B) The Mark III multiple cod-end bucket. (Reproduced with permission from Aron *et al*. 1964.) (C) ARIES. (Reproduced with permission from Dunn *et al*. 1993.) (D) A version of the LHPR. (Photograph courtesy of J. Smith, 1966.)

stalling of animals in the net which caused smearing of the distributions of animals and losses of animals from the recorder box. The modified LHPR was used without a net on the conning-tower of the US Navy research submarine *Dolphin* in the 1980s. Another modification of the LHPR was made by the British in 1980s. They used an unenclosed Lowestoft sampler to mount a pair of recorder boxes to collect meso- and micro-zooplankton. The system acoustically telemetered depth, flow, and temperature. It also carried a chlorophyll sensor with a recorder system. The LHPR was further modified for use in catching Antarctic krill. A descendant of the LHPR developed in the 1990s is the Autosampling and Recording Instrumental Environmental Sampler (ARIES) (**Figure 6C**). This cod-end plankton sampling device is a stretched version of the Lowestoft-modified Gull III frame. It has a multiple cod-end system, water sampler, data logger, and an acoustical telemetry system.

Multiple Net Systems

The development of multiple net systems began with the simple non-opening/closing Tucker trawl system. In the mid-1960s, timing clocks were used to open and close the Tucker trawl mouth. Then late in the 1960s, the British rectangular mouth opening trawl (RMT), which was opened and closed acoustically, was developed. The RMT was expanded into the NIO Combination Net (RMT $1+8$), which carries nets with $1\,m^2$ and $8\,m^2$ mouth openings (**Figure 7A**). This was expanded into a multiple net system with three sets of 1 m and 8 m nets controlled acoustically. The acoustic command and telemetry system for the RMT $1+8$ was replaced in the 1990s by a microcomputer-controlled unit connected by conducting cable to an underwater electronics unit.

In a parallel development in the 1970s, a five-net and a nine-net Tucker Multiple Net Trawl was developed on the West Coast of the USA. The system was powered electrically through conducting wire and controlled from the surface. A modified Tucker trawl system, the Multiple Opening/Closing Net and Environmental Sensing System (MOCNESS), with nine nets and a rigid mouth opening was built soon after on the US east coast (**Figure 7E**). The current versions of the MOCNESS are computer-controlled (**Table 2**). Sensors include pressure, temperature, conductivity, fluorometer, transmissometer, oxygen, and light.

The design of the Bé multiple plankton sampler (MPS) (**Figure 7B**), initially messenger operated in the late 1950s and then pressure-actuated in the 1960s, was the basis for the Bedford Institute of Oceanography Net and Environmental Sensing System (BIONESS), with 10 nets, developed in the 1980s (**Figure 7D**). A modified version of the MPS was developed in Germany at about the same time and named the Multinet; it carried five nets, which were opened and closed electronically via conducting cable (**Figure 7C**). A scaled-up version of BIONESS built in the 1990s was the Large Opening Closing High Speed Net and Environmental Sampling System (LOCHNESS). Another variant of the MPS was the Ocean Research Institute's (Japan) vertical multiple plankton sampler developed in the 1990s in which the nets are opened/closed by surface commands transmitted via conducting cable to an underwater unit.

Moored Plankton Collection Systems

Only a few instrument systems have been developed that autonomously collect time-series samples of plankton from moorings. Most were patterned after the CPR or LHPR (e.g. the O'Hara automatic plankton sampler built in the 1980s; a modified version of the O'Hara system built in the 1990s; the moored, automated, serial zooplankton pump (MASZP) built in the late 1980s) (**Figure 8**). The lack of such systems may be due to the difficulty of powering them for long periods underwater.

Optical Systems

Optical survey instruments can be divided into two categories, based on whether the systems produce an image of their zooplankton targets (e.g. video, photographic, and digital camera systems) or use the interruption of a light source to detect and estimate the size of particles (e.g. the optical plankton counter). The first attempts to quantify plankton optically appear to have been made in the 1950s using a beam of light projected into the chamber from a 300 W mercury vapor lamp and a Focabell camera (Orion Camera, Tokyo).

Image-forming Systems Mounted on Non-opening/Closing Nets

In the 1980s, a 35 mm still camera with a high-capacity film magazine in front of the cod-end of a plankton net attached to a rigid frame was used to take *in situ* silhouette photographs of zooplankton as they passed into the cod-end. This was a field application of the laboratory-based silhouette photography system developed in the late 1970s. The camera provided a series of photographic images at points along the trajectory of the net separated by <1 m. In the development of the ichthyoplankton recorder, the still camera was replaced

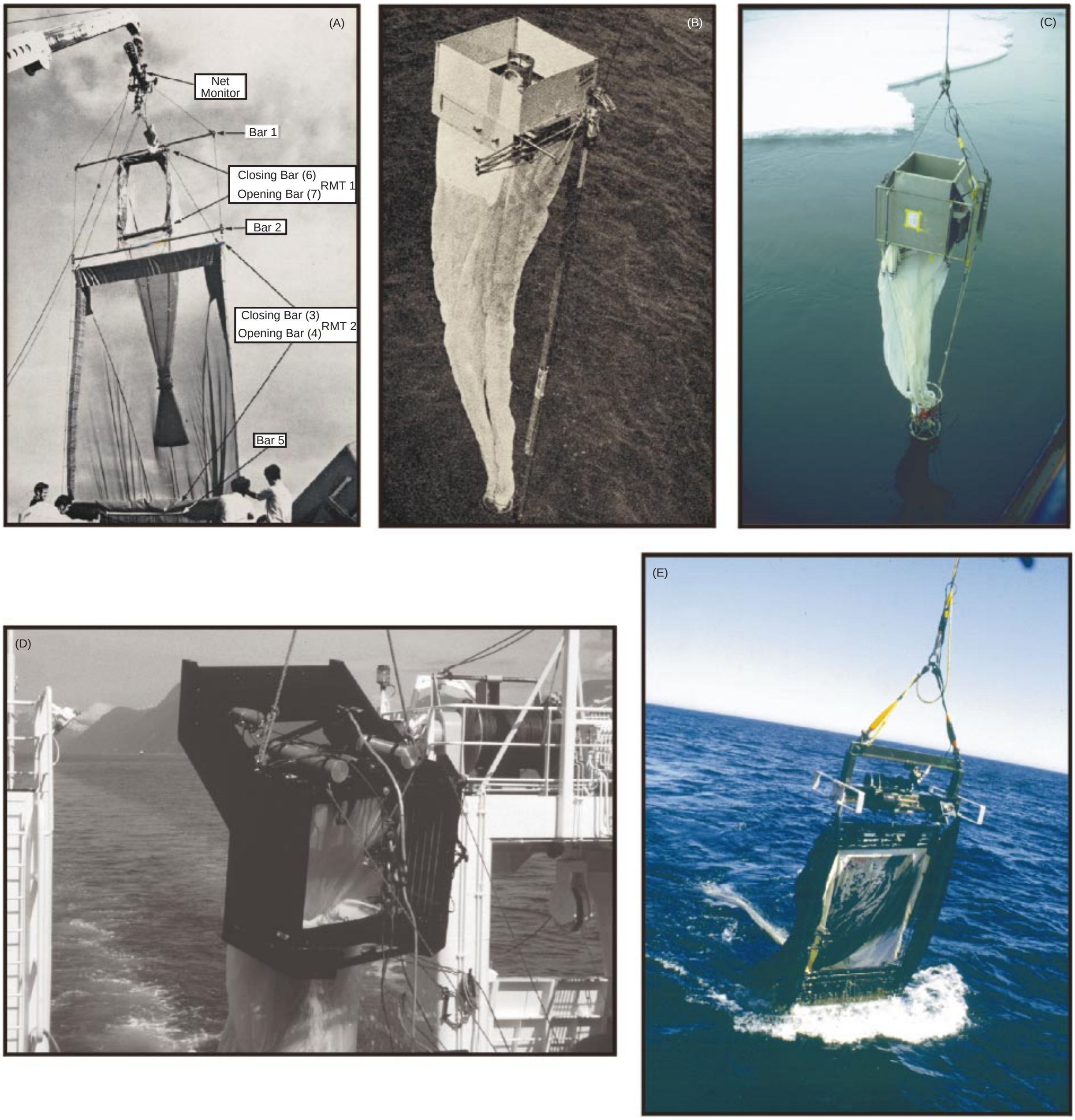

Figure 7 Some examples of multiple net plankton sampling systems. (A) The RMT 1 + 8. (Reproduced with permission from Baker, 1973.) (B) The Bé net. (Reproduced with permission from Bé, 1959.) (C) The Multinet. (Photograph courtesy of B. Niehof.) (D) The BIONESS. (Photograph courtesy of P. Wiebe, 1993.) (E) The 1 m^2 MOCNESS. (Photograph courtesy of Wiebe, 1998.)

with a video camera, which was located in front of the cod-end of a high-speed Gulf V-type net (*Nackthai*). It had an estimated horizontal spatial resolution of 3 cm. One consequence of going from camera film to video tape was a loss of image resolution.

Stand-alone Image-forming Systems

The video plankton recorder (VPR) was developed in the early 1990s as a towed instrument capable of imaging zooplankton within a defined volume of water (**Figure 9A**). The original VPR had four video cameras; each camera imaged concentrically located volumes of water ranging from 1 ml to 1000 ml, but it has been modified to a one- or two-camera system. It has been possible to image undisturbed animals in their natural orientations. The current VPR image processing system is capable of digitizing each video field in real time and scanning the fields for targets using user-defined search criteria

Table 2 MOCNESS system dimensions and weights

System	*Number of nets*	*Width of frame (m)*	*Height of frame (m)*	*Net width (m)*	*Mouth area at 45° towing angle (m)*	*Length of net (m)*	*Approx. weight in air (kg)*	*Rec. wire diameter (mm)*
MOCNESS-1/4	9	0.838	1.430	0.50	0.5	6.00	70	6.4
MOCNESS-1/4-Double	18/20	1.430	1.430	0.50	0.5	6.00	155	7.4
MOCNESS-1	9	1.240	2.870	1.00	1.0	6.00	150	7.4
MOCNESS-1-Double	18/20	2.560	2.870	1.00	1.0	6.00	320	12.1
MOCNESS-2	9	1.650	3.150	1.41	2.0	6.00	210	11.8
MOCNESS-4	6	2.140	4.080	2.00	4.0	8.44	460	11.8
MOCNESS-10	6	3.410	4.690	3.17	10.0	18.25	640	11.8
MOCNESS-20	6	5.500	7.300	4.47	20.0	14.50	940	17.3

The MOCNESS systems are denoted by the mouth area when being towed. Thus a MOCNESS-1/4 has a 0.25 m^2 mouth opening. The 'Double' systems have two sets of nets side-by-side in a single rigid framework. Nets can be opened and closed on one side and then opened and closed on the other.

for brightness, focus, and size. The targets are identified using a zooplankton identification program to provide near-real-time maps of the zooplankton distributions.

A number of VPR-based systems are currently in operation or under development: a single-camera system is mounted on the BIOMAPER II vehicle (described below); an internally recording VPR has been constructed and used to quantify radiolarians and foraminiferans; and one has been mounted on a 1 m^2 MOCNESS net system to map the fine-scale distributions of the larval cod prey items. A moored system called the Autonomous Vertically Profiling Plankton Observatory (AVPPO) utilizes an internally recording, two-camera VPR, and has been deployed in coastal waters off New England.

Image resolution constraints inherent in the use of standard video formats have driven the development

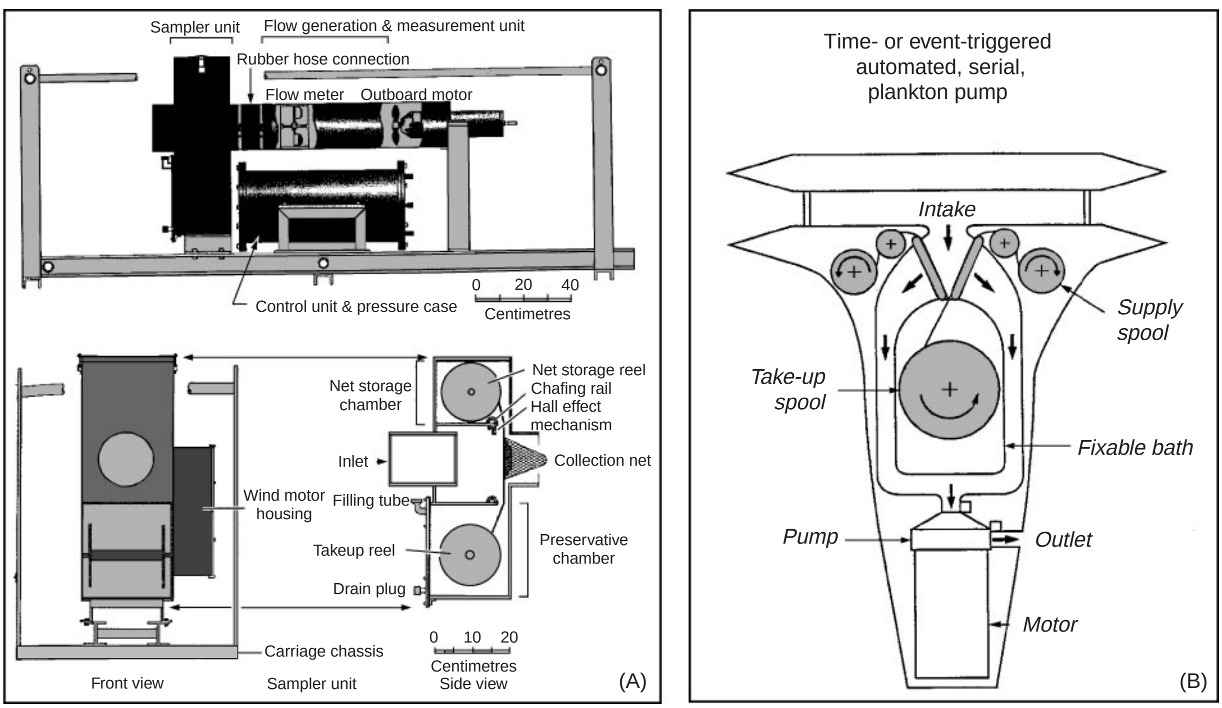

Figure 8 Two examples of moored plankton collecting systems. (A) A modified version of the O'Hara sampler. (Reproduced with permission from Lewis and Heckl, 1991.) (B) MASZP. (Reproduced with permission from Doherty *et al.* 1993.)

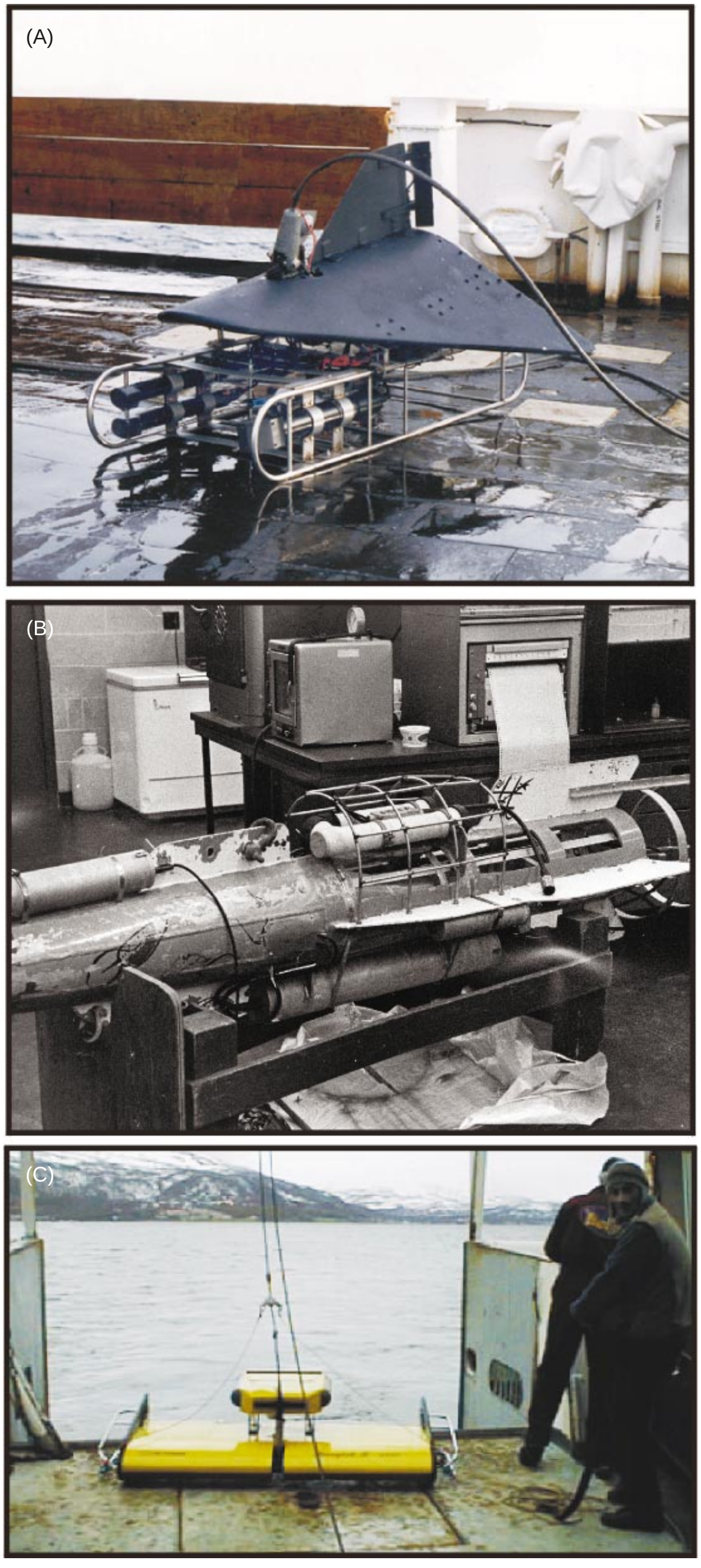

Figure 9 Examples of optical or electrical systems for collecting zooplankton data. (A) The VPR. (Photograph courtesy of P. Alatalo, 1999.) (B) The *in-situ* zooplankton detecting device. (Photograph courtesy of P. Wiebe, *c.* 1972.) (C) The optical plankton counter (OPC). (Photograph courtesy of M. Zhou, 2000.)

of optical systems that utilizes higher-resolution formats. A modification of the continuous underway fish egg sampler (CUFES, described below) utilizes a line-scanning digital camera to quantify the abundances of fish eggs. The shadowed image particle profiling and evaluation recorder (SIPPER) utilizes high-resolution digital line-scanning cameras to quantify zooplankton passing through a laser light sheet. The SIPPER has been mounted either on a towed vehicle called the high-resolution sampler (HRS) or an AUV.

The need for systems to quantify the abundance of 'marine snow' prompted development of profiling systems based on both still and video cameras. In the 1980s, a profiling system called the large amorphous aggregates (LAA) camera was constructed which employed a photographic camera and a pair of strobes to photograph marine aggregates. A video profiling instrument called the underwater video profiler (UVP) has been used to quantify the vertical distribution and size frequency of marine snow, and to examine the distributions of macrozooplankton. The UVP consists of a Hi-8 video camera imaging a collimated light sheet coupled with a CTD, data logger, and batteries. A profiling system called ZOOVIS recently has been developed around a high resolution (2048×2048 pixel) digital camera and CTD linked to a surface workstation via a fiber-optic cable. A color video camera has been mounted on the front of a Sea Owl II remotely operated vehicle (ROV) and used to quantify the vertical distribution of gelatinous zooplankton off the west coast of Sweden.

Still holographic imaging of plankton in a laboratory was first reported in 1966. It was refined in the 1970s to record movies of live plankton in the laboratory. In the 1990s, a submersible internally recording in-line holographic camera that records up to 300 holograms on a film emulsion was developed.

Many zooplankton produce or induce the production of bioluminescent light that can be detected with sensitive CCD cameras. One system is mounted on the Johnson SeaLink manned submersible and consists of an intensified silicon-intensified target (ISIT) video camera mounted on and aimed forward at a 1 m diameter transect screen to quantify the distribution, abundance, and identities of bioluminescent zooplankton.

Particle Detection Systems

Particle detection systems refer to non-image-forming devices that utilize interruption of an electrical current or a light beam to detect and estimate the size of a passing particle. The first *in situ* particle counting and sizing system appeared in the late 1960s and was referred to as the *in situ* zooplankton detecting device (**Figure 9B**). A shipboard version of the device was connected to a continuously pumped stream of water and employed to analyze spatial heterogeneity of zooplankton in surface waters in relation to chlorophyll fluorescence and temperature. A version of this conductive zooplankton counter was deployed aboard a Batfish towed vehicle in the 1980s.

A second group of particle detectors utilized photodetectors rather than changes in voltage. The Opto-Electronic Plankton Sizer was a laboratory-based system designed in the 1970s to automate the measurement of preserved plankton samples. The HIAC particle size analyzer was modified at the Lowestoft Laboratory during the late 1970s for plankton counting. The optical plankton counter (OPC) was developed during the mid-1980s (**Figure 9C**). This instrument measures changes in the intensity of a light beam that occur when a particle crosses the beam. The OPC has been mounted on a variety of towed platforms or in shore-based or shipboard applications. The OPC has also been incorporated into a shipboard device called the continuous underway fish egg sampling system (CUFES) which enumerates the distribution and abundance of fish eggs in surface waters. In spite of the prevalence of OPC systems in current use, interpretation of OPC data remains a subject of some controversy.

Optical Instruments for Nonquantitative Studies

The ecoSCOPE is an optical video-endoscope that enables direct observation of predator–prey interactions between juvenile fish and zooplankton. The ecoSCOPE has been operated from an ROV, from the keel of a sailing vessel, and in towed and moored modes, but the best recordings of predator/prey interactions have come from free-drifting deployments, when the instrument was hovering within schools of feeding juvenile herring. A software package called dynIMAGE animates sequential images keeping the fish and its prey in the middle of the viewing field.

Optical sensors can provide valuable groundtruthing for acoustical sensors. In the 1990s, a megapixel digital still camera was mounted on a FishTV sonar array and the resulting system was named the Optical-Acoustical Submersible Imaging System (OASIS). In this system, high acoustic returns are used to trigger the camera taking a picture of the acoustical target. An analog video camera aimed at the focal point of an acoustic array mounted on the front of a MAXRover ROV has been used to take pictures of individual zooplankton passing through the acoustic beam.

High-frequency Acoustics

High-frequency acoustics ($\geq$38–1000 kHz) provide the foundation for another class of tools to study zooplankton. The utility of the acoustic systems derives from their ability to operate with high ping rates and precision range-gating. Mapping planktonic distributions on a wide range of space and timescales is becoming possible because of the continued development of acoustics systems and appropriate ground-truthing methods. There are two fundamental measurements: volume backscattering (integration of the energy return from all individuals in a given ensonified volume, i.e. echo integration) and target strength (echo strength from an individual). Statistical procedures have been developed to estimate animal assemblage size distribution using the data from single-beam transducers. In some cases, it is possible to extract estimates of animal target strength distribution in addition to volume backscattering from a series of single-beam transducers operating at different frequencies. Multibeam acoustical systems provide a direct means of determining individual target strength (TS). The two current designs, dual-beam and split-beam, both provide a hardware solution to the problem of TS determination.

The Current State of Plankton Sampling Systems

The diversity of zooplankton samplers in use today reflects the fact that no single collection system adequately samples all zooplankton. Non-opening/closing nets, such as the WP2, the modified Juday net, and the Bongo net, are used in large ocean surveys. Simple, double-messenger opening/closing nets similar to those developed in the first half of the last century are still manufactured and used. The Multinet, RMT 1 + 8, BIONESS, and MOCNESS are widely used multiple-net systems that also carry additional sensors to measure other water properties. Plankton pumps are also being used, especially to collect micro-zooplankton.

The advent of high-speed computers and towing cables with optical fibers and electrical conductors have enabled development of multi-sensor towed systems which provide real-time data while the instrument package is deployed. The MOCNESS has been equipped with a high-frequency acoustic system for forward or sideways range-gated viewing (**Figure 10A**). An EG&G Edgerton model 205 camera and a flash light were mounted on the top of a modified MOCNESS and on the top of BIONESS to take black and white photographs about 2 m in front of the net mouth. The BIONESS has also been equipped with an OPC and video lighting system, and used in conjunction with an echosounder.

The BIo-Optical Multi-frequency Acoustical and Physical Environmental Recorder – BIOMAPER II – was developed to conduct high-speed, large-area surveys of zooplankton and environmental property distributions to depths of 500 m (**Figure 10B**). Mounted inside are a multi-frequency sonar (upwards-looking and downwards-looking pairs of transducers operating at five frequencies: 43, 120, 200, 420, and 1000 kHz), an environmental sensor package (CTD, fluorometer, transmissometer), and several other bio-optical sensors (down- and upwelling spectral radiometers, spectrally matched attenuation, and absorption meters). A single-camera video plankton recorder (VPR) system is mounted above and just forward of the nose piece. The lower four acoustical frequencies involve split-beam technology and are able to make target strength and echo integration measurements.

A variety of vehicles have been built that actively change their vertical position without changing the towing wire length. Examples for surveying zooplankton include the undulating oceanographic recorder and SeaSoar equipped with optical (VPR and OPC) and/or acoustical (the Tracor Acoustical Profiling System, TAPS). Remotely operated vehicles (ROVs) have also been equipped with acoustical and video systems to study zooplankton. A SeaRover ROV was equipped with the same dual-beam acoustic system and environmental sensors. A VPR rigged to provide 3-D images of plankton and an environmental sensor package (temperature, conductivity, pressure, fluorescence) were mounted on the front of the ROV JASON and on the SeaRover ROV (**Figure 10C**). FishTV (FTV) has been used on a Phantom IV ROV and a combination of acoustics and video has been used on the front of a MAXRover ROV. Dual-beam acoustics (420 and 1000 kHz) have also been deployed on the DSRV Johnson SeaLink.

Future Developments

The future promises vastly increased application of remote sensing techniques and sensor development, and real-time data telemetry, processing, and display. Three-dimensional (space) and four-dimensional visualization (space and time) of biological and acoustic data are also an increasingly important aspect of data processing. For a number of research

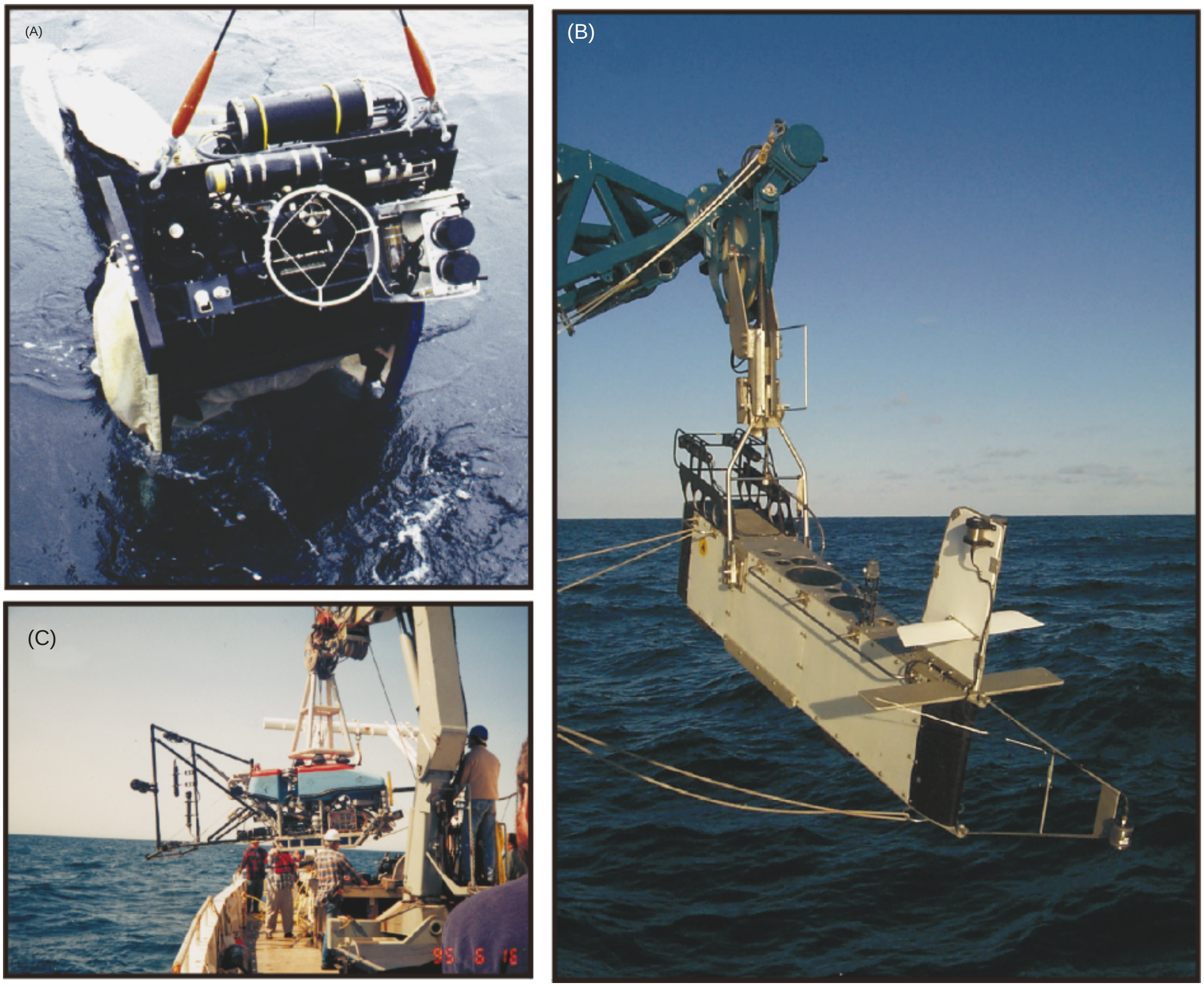

Figure 10 Examples of multi-sensor plankton sampling systems. (A) MOCNESS with a dual-beam acoustic system. (Photograph courtesy of P. Weibe, 1994.) (B) BIOMAPER-II. (Photograph courtesy of P. Wiebe, 1999.) (C) The JASON-ROV with 3-D VPR system. (Photograph courtesy of P. Alatalo, 1995.)

programs today, the development of an image of the spatial arrangement of organisms is but the first step in efforts to study and understand their relationships to each other and to their environment. Thus, there is need for real-time 3-D and 4-D images.

Autonomous self-propelled vehicles (AUVs) have only recently begun to be used widely to gather oceanographic data. The remote environmental measuring units (REMUS) are a new class of small AUVs which can carry an impressive array of environmental sensors including a VPR. Another class of autonomous vehicles is epitomized by the autonomous benthic explorer (ABE), which is equipped with precise navigation and control systems that enable it to descend to a worksite, navigate preset tracklines or terrain-follow, and find a docking station. A much larger AUV which has been employed for biological studies is the Autosub-1 that carries a gyrocompass, ADCP, an echosounder, and acoustic telemetry and surface radio electronics. It can be programmed to run a geographically based course using GPS surface positions and dead reckoning.

The autonomous Lagrangian circulation explorer (ALACE) and the more recently developed profiling version (PALACE) floats that carry temperature and conductivity probes are vertically migrating neutrally buoyant drifters. They track the movements of water at depths between the surface and 1000–2000 m depth. Hundreds to thousands of the PALACE floats will be deployed over the next few years and it is expected that they will become a mainstay in the Global Ocean Observing System (GOOS). The next generation of neutrally buoyant floats is an autonomous glider named SPRAY. SPRAY will be able to sail along specific preprogrammed tracklines. A further step in their development is to provide biological instrumentation to complement the physical sensors.

High-resolution optical systems, such as the VPR, combined with computer-based identification programs can now provide higher level taxa identifications in near-real time. Classification of species using acoustic signatures is less well developed and it now seems unlikely that the technology to develop species-specific acoustic signatures will be developed soon. Molecularly based species identification is likely to make significant strides in the next decade. It is now conceivable that this information will enable simultaneous analysis, identification, and quantification of all species occurring in a zooplankton sample.

See also

Acoustic Scattering by Marine Organisms. Autonomous Underwater Vehicles (AUVs). Continuous Plankton Recorders. Grabs for Shelf Benthic Sampling. Marine Snow. Plankton. Satellite Remote Sensing SAR. Sea Ice: Overview; Variations in Extent and Thickness.

Further Reading

Harris RP, Wiebe PH, Lenz J, Skjoldal HR and Huntley M (eds) (2000) *ICES Zooplankton Methodology Manual*. New York: Academic Press.

Kofoid CA (1911) On a self-closing plankton net for horizontal towing. *University of California Publications in Zoology* 8: 312–340.

Miller CB and Judkins DC (1981) Design of pumping systems for sampling zooplankton with descriptions of two high-capacity samplers for coastal studies. *Biol. Oceanogr*. 1: 29–56.

Omori M and Ikeda Y (1976) *Methods in Marine Zooplankton Ecology*. New York: John Wiley & Sons.

Schulze PC, Strickler JR, Bergström BI *et al*. (1992) Video systems for in situ studies of zooplankton. *Arch. Hydrobiol. Beih. Ergebn. Limnol*. 36: 1–21.

Sprules WG, Bergström B, Cyr H *et al*. (1992) Non-video optical instruments for studying zooplankton distribution and abundance. *Arch. Hydrobiol. Beih. Ergebn. Limnol*. 36: 45–58.

Tranter DJ (ed.) (1968) *Part I. Reviews on Zooplankton Sampling Methods. Monographs on Oceanographic Methodology, Zooplankton Sampling*. UNESCO.